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Effect of number of laser pulses on p^+/n silicon ultra-shallow junction formation during non-melt ultra-violet laser thermal annealing

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ABSTRACT

We investigate the effect of the number of laser pulses on the formation of p^+/n silicon ultra-shallow junctions during non-melt ultra-violet laser (wavelength, 355 nm) annealing. Through surface peak temperature calculating by COMSOL Multiphysics, the non-melt laser thermal annealing is performed under the energy density of 130 mJ/cm^2. We demonstrate that increasing the number of laser pulses without additional pre-annealing is an effective annealing method for achieving good electrical properties and shallow junction depth by analyzing sheet resistance and junction depth profiles. The optimal number of laser pulses is eight for achieving a high degree of activation of dopant without further increase of junction depth. We have also explained the improved electrical characteristics of the samples on the basis of fully recovered crystallinity as revealed by Raman spectroscopy. Thus, it is suggested that controlling the number of laser pulses with moderate energy density is a promising laser annealing method without additional pre-annealing.

1. Introduction

Deeply scaled complementary metal oxide semiconductor (CMOS) technologies require ultra-shallow junction (USJ) formations with low resistance and abrupt profiles to decrease short-channel effects. The junction depth for each technical node is specified in the International Technology Roadmap for Semiconductors [1]. Over the past several years, the optimization of vertical and lateral diffusion of source/drain doping profiles has attracted increasing attention. In order to form shallow junction profiles, low-energy ion implantation and plasma doping (PLAD) are widely used to introduce dopant into a semiconductor wafer [2,3]. After implantation, Flash-lamp annealing (FLA) and spike-rapid thermal annealing (RTA) are used to activate dopants [4,5]. However, FLA and spike-RTA are not suitable method for forming USJ with high activation level because of their long annealing time. In particular, it is more difficult to form p^+/n USJ using boron ion as compared to $n^{+/}p$ USJ due to the transient-enhanced diffusion (TED) [6,7]. Therefore, laser thermal annealing (LTA) is promising substitute for the conventional annealing process as it drastically reduces annealing time and increases annealing temperature. Various reports have been published on LTA over a long period of time [8–10]. Excimer [11], CO_2[12], and solid-state lasers [13] of various wavelength have been used to activate the dopant in p^+/n junction. However, high laser energy density is needed to activate the dopant during these one-pulse LTA processes. For this reason, the surface of silicon is melted and the dopant is redistributed within the molten layer. Therefore, non-melt laser annealing is needed to effectively form USJ. Because one-pulse laser has insufficient energy to activate the dopant under non-melt condition, non-melt laser annealing combined with low-temperature RTA is an effective method for achieving a shallow junction depth and a low sheet resistance simultaneously [14]. However, combining LTA with pre-annealing complicates the overall annealing process. Therefore, we attempted to achieve an optimized USJ with low sheet resistance by controlling the number of laser pulses without pre-annealing. We investigated how the number of pulses under non-melt ultraviolet (UV) laser annealing affected dopant activation and diffusion by analyzing experimental data and temperature profiles obtained by analytical calculation. The sheet resistances of the non-pre-annealed and pre-annealed samples subsequently irradiated by UV laser were compared to determine the optimal number of laser pulses. It is also discussed about the phenomenon of dopant activation through Raman crystallinity.

2. Experimental details

A 10-Ωcm n-type Si (100) wafer was prepared in order to form the

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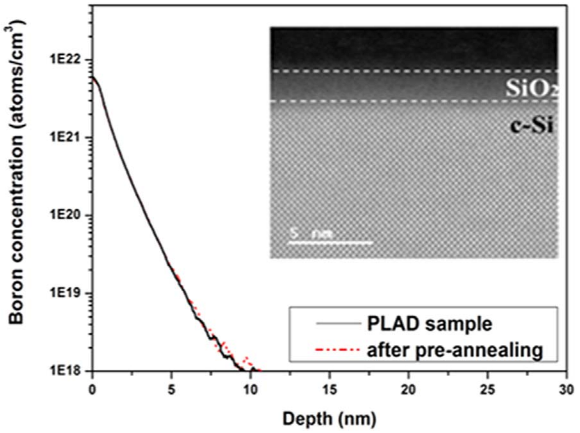

Fig. 1. ToF-SIMS depth profiles for PLAD and pre-annealed samples. The inset is a cross-sectional TEM image of a PLAD sample.

Table 1
Heating and cooling ramp of UV laser for several energy densities.

UV laser (mJ/cm^2)	Heating ramp (K/ns)	Cooling ramp (K/ns)
800	121	33
110	167	46
130	195	53
140	210	58

Table 2
Parameters for sample used in heat calculation.

	Silicon
c: Specific heat capacity [J/(kg·K)]	680 (liquid), 710 (solid)
ρ: Density of silicon [kg/m^3]	2500 (liquid), 2330 (solid)
K: Thermal conductivity [W/(m·K)]	200 (liquid), 148 (solid)
R: Reflectivity	0.5654 (UV laser, 355 nm)
α: Absorption coefficient [1 /m]	1.04 × 10^8 (UV laser, 355 nm)
δ_a: Absorption depth [nm]	9.6154
Emissivity of silicon	0.27 (liquid), 0.66 (solid)
Melting temperature of c-silicon [K]	1690
Latent heat of fusion [J/g]	1650
Heat transfer coefficient [W/(m^2·K)]	10

p$^+$/n junction. After conventional cleaning of the wafer, boron ions were introduced using the low-energy BF$_3$ plasma- immersion ion-implantation (PIII) technique [APTC, APIS200]. The plasma-doping energy and dose were 500 eV and 1.2×10^{15} /cm^2, respectively. The inset of Fig. 1 shows a cross-sectional transmission electron microscopy image of samples of a PLAD sample. We confirmed that the PLAD process hardly form an amorphous layer on the substrate in this condition. After PLAD process, we prepared pre-annealing sample and non-pre-annealing sample. The pre-annealing was performed at 500 °C for 10 s using rapid thermal annealing system with a 30 °C/s heating ramp rate. As observed from Fig. 1, RTA under these conditions also did not affect the dopant depth profile. The samples were treated with a buffered oxide etch for 30 s to remove native oxide. The samples were then irradiated using the third harmonic of a 355-nm-wavelength neodymium-doped yttrium aluminum garnet (Nd^{3+}:YAG) ultraviolet (UV) laser (Quantel, Q-smart). The laser pulses were produced at a repetition frequency of 10 Hz and the pulse duration employed was 5 ns. A flat-top laser beam intensity profile and a 5 mm×5 mm beam spot were used to increase the surface temperature uniformity so that it was comparable with that predicted by a Gaussian profile. The experimental setup is schematically shown in Fig. 2. The laser energy densities and number of pulses were selected between 80–140 mJ/cm^2 and 1–10, respectively. And the heating and cooling ramp of UV laser are shown in Table 1.

To determine the laser energy density in which the surface melts, the surface morphology was characterized through atomic force microscopy (AFM) [XE-100] and a field emission scanning electron microscopy (FESEM) [JSM-7100F, JEOL]. In order to investigate how LTA affected the dopant concentration profiles, boron depth profiles were obtained by time of flight secondary ion mass spectrometry (ToF-SIMS) in dual-beam mode [Ion ToF, ToF-SIMS 5]. For boron detection sputtering was accomplished by O$_2^+$ at energy 500 eV and current 75.8 pA. The sputtering raster was 300×300 µm^2, while the analysis was made in positive modality by using Bi$^+$ primary ion beam operating at, 30 keV and current 5.16 pA, rastering over 100×100 µm^2. Both beams hit the target at an incident angle of 45°. The pressure of main chamber was 2×10^{-8} bar. Dopant activation was evaluated from the sheet resistances (R$_s$) that were measured using a 4-point probe system [AIT, CMT-SR2000N], and the sample crystallinities were characterized using Raman spectroscopy with Nd: YAG 532 nm laser [HORIBA, LabRam ARAMIS] technique. Excitation laser beam was focused into a spot with diameter 20 µm at which its power was 5 mW.

3. Simulation procedure

The temperature distribution throughout the sample irradiated by a flat-top laser beam was numerically analyzed using COMSOL Multiphysics V5.2 [15,16]. The transient temperature distribution in laser-irradiated materials is not only due to heat diffusion but also to

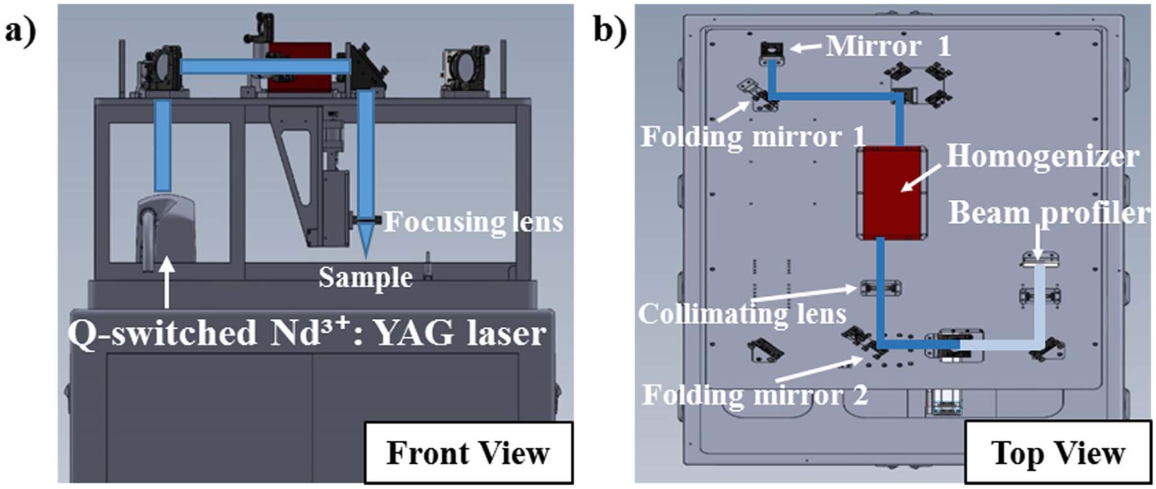

Fig. 2. Experimental setup for laser annealing of p$^+$/n junction with homogenizer.